Effects of Sound on the Marine Environment: Rapid Assessment

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LONG-TERM GOALS

To develop novel techniques to predict the impact of sound on the marine environment and use natural sound sources (such as whale calls) to observe non-invasively both animal behavior and the marine environment.

OBJECTIVES

The main objective is to develop an acoustic simulation package that can duplicate signals received in the ocean from Navy SONAR systems. This involves including: extensive 3-D environmental data into state-of-the-art acoustic propagation models, information about source and receiver (marine mammal) motion and signal waveforms from commonly used navy SONAR sources. The acoustic models are modified as needed to provide for directional sources and allow for Monte-Carlo simulations to quantify the variability. The models are tested in particular sites to both demonstrate the end-to-end processing and validate the algorithms.

Another objective is to advance algorithms for tracking calling marine mammals through acoustic techniques. The most common approach for passive acoustic localization of mammals, hyperbolic fixing, has limited accuracy in environments where refractive and multipath effects are important. However, a new localization algorithm based on acoustic propagation modeling was developed to exploit these multipath effects for improved localization accuracy at longer ranges. The model-based algorithm has been tested against data from two Navy ranges in tracking two whale species with markedly different call characteristics.

APPROACH

The authors have participated in several workshops and the ESME group has collectively converged on the important features for an acoustic simulation package. A variety of options are required that depend on environmental conditions, run-time, desired output (e.g. waveform vs. intensity) and source

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14. ABSTRACT
To develop novel techniques to predict the impact of sound on the marine environment and use natural sound sources (such as whale calls) to observe non-invasively both animal behavior and the marine environment.

15. SUBJECT TERMS

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characteristics. For some applications it is expected that maximum sound intensity predictions computed rapidly over large areas are needed and in others the acoustic waveform as received by a mammal moving through the water is required. The approach is to use both ray/beam and normal mode theory models to make the propagation predictions. Each has advantages under different circumstances. The ray model is well suited for generating broadband acoustic responses especially for arbitrary waveforms and moving platforms such as marine mammals. The normal mode model lends itself to a pre-computation stage and this allows rapid calculations of 3-D transmission loss fields that can be updated as the source and receivers move through the environment.

In collaboration with Chris Tiemann (SAIC) and with additional support from the CEROS program, we have obtained acoustic data from the Pacific Missile Range Facility (PMRF) during the humpback whale, winter breeding season. We have also obtained seismometer data from the Southern California Offshore Range (SCORE) through collaboration with John Hildebrand (SIO); blue whales migrating along the California coast can be heard in that data set. The model-based localization algorithm was applied to both data sets, and it successfully localized whales in both locations. Further tests of the algorithm will be possible using data from a controlled source experiment at the Navy's Atlantic Undersea Test and Evaluation Center (AUTEC) range.

WORK COMPLETED

In this fiscal period, work has been completed on two modules for the ESME acoustic simulation package: a 3-D acoustic time series stimulator and a 3-D Coupled Normal Mode model. Additional work has been completed in conjunction with the ONR, DRI "Capturing Uncertainty in the Common Tactical Environmental Picture" on computing error bars for transmission loss predictions and on Rapid Environmental Assessment methods that reduce the variance in transmission loss predictions by making better estimates of the propagation environment.

RESULTS

1. 3-D Acoustic Time Series Stimulator

Probably the most critical factor for acoustic modeling is accurately predicting the sound level (transmission loss) at different locations in the ocean. However, the research community is actively investigating how sound interacts with the mammals auditory functions to determine the important factors that might be damaging. In addition to level there may be beat patterns or frequency combinations that are particularly harmful. The approach is to stimulate a finite element model of the mammal head with the acoustic time-series, as it would be received in a realistic scenario. This acoustic stimulator needs to produce a received acoustic field as it evolves in time and include source functions (for typical Navy SONAR systems) and information about the mammal motion. The mammal motion is important to correctly account for Doppler shifts and interference patterns in the received time-series. The marine biology team is providing the ESME group with information about how different marine mammals move through the ocean (e.g. diving patterns) and this is incorporated into the acoustic stimulator.

The acoustic stimulator is based on the Bellhop ray/beam propagation model. This model is well suited for this application for several reasons: (1) a single ray trace produces arrival amplitudes and delays, which contains all the information in the broadband channel impulse response. This representation allows for either narrow or broadband sources at low or high frequencies. (2) The arrival amplitudes and delays are extremely well behaved and lend themselves to interpolation. This allows a relatively course sampling grid to be used in the ray trace calculation yet produce accurate time-series predictions for even small movements through the environment. (3) Bellhop can treat range-dependent environments as either Nx2D or fully 3-D. This allows for as much information about the environment (e.g. bathymetry, sound speed profiles) to be included in the acoustic models.

As an example, in Fig. 1 (a) the received time-series is shown for a mammal moving near the surface and away from a 3500 Hz signal (source starts at 0 seconds). In Fig. 1 (b) the frequency domain representation of the field is given showing the Doppler shifted signal. Each ray path is Doppler shifted by an amount that depends on the relative direction between ray and mammal motion. With this approach, long time-series can be developed and the effect of different signal types and duty cycles can be studied.

(a) (b)

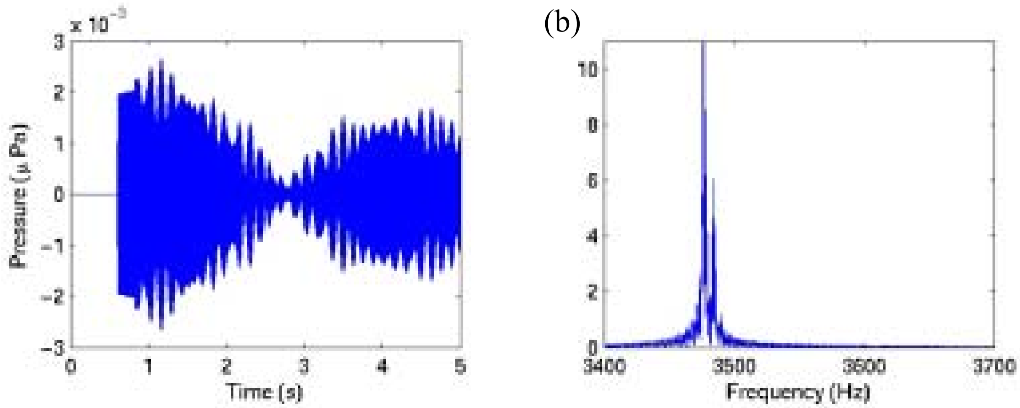
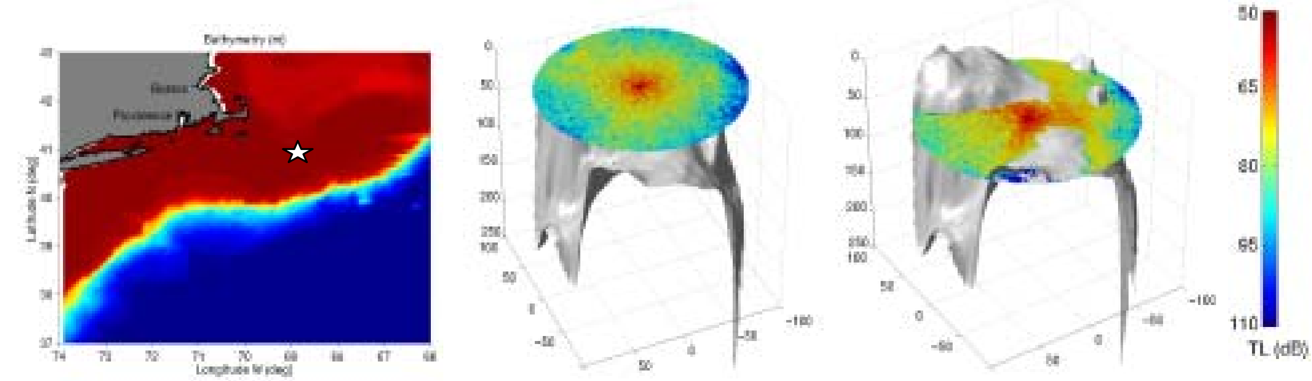


Figure 1: Left panel shows the time series for a 3500 Hz signal as received by a mammal moving away from the source (at about 1 km range). Right panel shows the Doppler shifted received spectrum.

2. 3-D Coupled Normal Mode Model

An acoustic stimulator that gives accurate time series predictions about the field from the SONAR to the mammal may not be required for all applications. It is likely that a propagation model that rapidly predicts the sound level (transmission loss) in 3 dimensions (or Nx2D) will be needed to determine safe operating areas. The 3-D normal-mode model is particularly attractive for this application. In brief, it has the unique characteristic amongst the various models that it is divided between a lengthy pre-computation stage (to calculate the local normal modes) and an extremely rapid final stage in which the modes are combined to calculate acoustic levels. In the latter stage one can dynamically move sources (ships) and receivers (marine mammals) through the environment to do extensive simulations of acoustic impact under a variety of conditions.

In Fig. 2 (a), the bathymetry is shown for one of the ESME test regions off the Northeast coast of the United States. For a 3-D transmission loss prediction, this modeling tool first determines the minimum and maximum water depth for the region and computes all the normal mode functions needed to span these depths. The pre-computation of the mode functions is usually the most time consuming process in the calculation but this depends on the variability of the environment. Next, the environment for each bearing is extracted and the mode functions are selected and aligned to correspond. The acoustic field along that bearing is determined through a series of matrix multiplies that performs the projection of each mode set onto the adjacent one. The final step is to extract the field at the desired depth points. Forming the propagation as a series of matrix multiplies is extremely efficient and allows for a complete 3-D acoustic field to be generated in seconds on a desktop PC. In Fig. 2 (b) and (c), an example of the transmission loss (TL) is shown (TL is overlying the bathymetry) using this method for slices at two depths for a 400 Hz source. Using this type of 3-D transmission loss modeling, the sound level for a given area and for a particular SONAR system can be rapidly determined.



(a) (b) (c)

Figure 2: Bathymetry and coastline are shown in panel (a) along with a circle showing the area being modeled. In panels (b), and (c) the 3-D transmission loss is shown over bathymetry for slices at 10 and 100 m depths.

3. Error Bars on Transmission Loss Predictions

Error bars on acoustic levels are particularly important for this application. The end-user of the acoustic simulation tools is principally interested in making policy or operational decisions based on the predicted acoustic impact. He or she is not necessarily an expert on all the physics that goes into calculating that acoustic level. However, intelligent decisions require an understanding also of the error bars on that prediction. For instance, in some cases one may prefer to deploy an acoustic system in an area with greater predicted acoustic impact, because the confidence in the prediction is much higher than an alternative location. More broadly, an understanding of where reduction in the uncertainties (e.g. bottom information, mammal thresholds, oceanographic information) has the greatest effect is a guide to where resources should be expended to improve the predictions.

We have developed a ray-based interpolation technique for computing TL that can be used with Monte-Carlo methods since run times are reduced factors of 50-1000. Using Monte-Carlo methods error bars can be estimated by calculating TL over thousands of realizations of the environment (e.g. seabed types). With adequate sampling of the possible environmental values the bounds on TL (variance) can be determined. Ray based propagation models are common in the SONAR community but usually a new ray trace is required each time environmental conditions change. Even though ray methods are computationally fast, if thousands of calculations are needed the costs become significant. Here, ray calculations are made only for the extreme values for each of the environmental parameters (e.g. 6 ray calculations for 3 seabed parameters). The well-behaved ray arrival amplitudes and delays are then interpolated for each random set of parameters drawn in the Monte Carlo simulation. The TL, at each frequency ω, is then calculated by summing over all arrival amplitudes (A_n) and delays (t_n) according to, $TL(\omega) = -20\log\left|\sum_{n=1}^{Narr} A_n \exp(i\omega(t-t_n))\right|$.

A second thrust of this research is to develop tools for Rapid Environmental Assessment (REA) to determine, for example, the acoustic properties of the seabed. Of the many factors that can contribute to TL variance the seabed properties are probably the least well known. These REA tools will provide the environmental characterization needed for accurate propagation predictions. In addition, the environmental imaging will be done to have a minimal impact placing emphasis on ocean and sub-bottom tomography using passive rather than active sources such as ships of opportunity.

4. Model-based mammal localization

The passive acoustic localization of marine mammals is of interest to those wishing to minimize the effects of sound on such animals, but traditional techniques of doing so can suffer from inaccuracies in environments where acoustic multipath effects are important. Using acoustic data from a widely distributed array of receivers at PMRF, a new localization algorithm based on the ray/beam acoustic propagation model Bellhop was developed, and it successfully localized singing humpback whales in the area. The algorithm uses comparisons between predicted and measured time-differences of arrival between widely spaced receivers to build an ambiguity surface, like that shown in Fig. 3a, showing the most likely whale position in a plan view around an array.

The same algorithm was then applied to seismometer data near the SCORE range, where it successfully localized blue whales migrating through the area. Repeated localizations over time can build tracks of whale movement, as shown in Fig. 3b. The robustness of the localization algorithm is demonstrated in its ability to perform in an environment other than that for which it was initially designed, tracking animals with significantly different call characteristics.

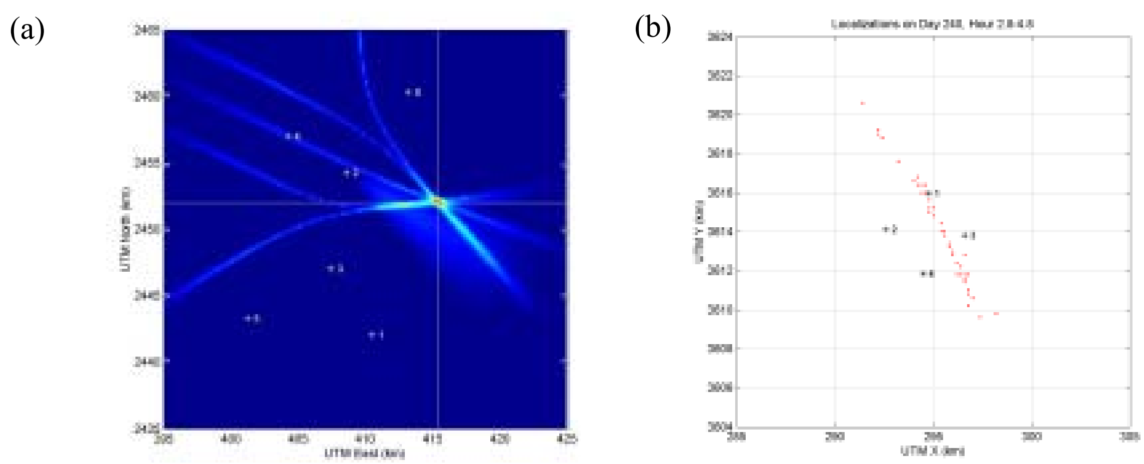


Fig 3. (a) A peak on an ambiguity surface generated by the model-based localization algorithm identifies humpback whale positions on a planview around the PMRF array. (b) Repeated localizations track a blue whale moving over an array of seismometers near the SCORE range.

IMPACT/APPLICATIONS

This work is intended to develop a state-of-the-art simulation system to predict the effects of sound on the marine environment. There is at least scattered evidence that anthropogenic sound is affecting the behavior of marine mammals. The major source is probably commercial shipping; however, modern active SONAR may also be disturbing or even dangerous to marine mammals. This research reflects increasing sensitivity to activities potentially affecting the marine environment.

TRANSITIONS

The acoustic modeling tools are being integrated by the NRL team in the baseline simulator destined for transition to OPNAV N45.

RELATED PROJECTS

The Center for Excellence in Research on Oceanographic Sciences provided additional support for the whale tracking effort at the Pacific Missile Range Facility including the development of the real-time data acquisition system. The ESME research is jointly supported with the ONR Marine Mammal Program.

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